VALIDATION OF THE *INSTANT BLOOD PRESSURE* APP

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Abstract

Introduction: The application of portable technology to healthcare is known as mobile health ('mHealth'). *Instant Blood Pressure* (IBP) is an mHealth app that measures blood pressure (BP) using the internal sensors in an iPhone, no cuff required. It was a popular app and user reviews document its use in management of hypertension and other BP-related conditions. It has never been independently validated.

Methods: We enrolled adults from 5 ambulatory clinics in 2015, excluding those with an internal device, active arrhythmias, or who were unable to use the app. Participants guessed their BP then had two order-randomized pairs of BP measurements taken from IBP and a sphygmomanometer ('standard' measurement). Mean absolute differences for BP were calculated comparing each IBP measurement to an average of the two standard measurements. We also calculated mean relative differences (IBP minus standard), British Hypertension Society (BHS) accuracy grading, and sensitivity and specificity for the detection of hypertensive measurements. Mean absolute differences and mean relative differences were calculated for successive same-device BP measurements. We regressed systolic and diastolic BP on IBP on age, sex, height, weight, and HR.

Results: Of the 85 participants, 52% were women, mean (SD) age was 56.6 (16.3) years, BMI was 27.6 (5.7) kg/m^2; 53% self-reported hypertension. Mean absolute difference was 12.4 (10.5) mm Hg for systolic and 10.1 (8.1) mm Hg for diastolic. Mean relative difference was -1.2 (16.2) mm Hg for systolic and 7.1 (10.8) mm Hg for diastolic. IBP achieved the lowest possible BHS accuracy grades. Sensitivity and specificity of IBP for detection of hypertensive-range BP were 0.22 and 0.92. For BP, successive IBP measurements varied less than successive standard measurements. Regression analysis found that 68% and 85% of the variability of IBP systolic and diastolic BP results were attributable to age, sex, height, and weight and HR.

Conclusions: BP measurements from an mHealth app with >148,000 copies sold were inaccurate. The low sensitivity for detection of hypertension means that 78% of hypertensive BPs were misclassified as

non-hypertensive. We suspect that the algorithm may derive its results from population curves of BP for entered age, sex, height, and weight.

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Introduction

Mobile health ('mHealth') technology is broadly defined as the application of portable technology to health care. It has grown in popularity with the smartphone revolution. Fifty-eight percent of mobile users[1] have downloaded at least one of the >165,000 mHealth applications ('apps') available on the Google Play and Apple iTunes app stores. While the majority of these apps are wellness-oriented (e.g., diet and exercise trackers),[2] many mHealth apps have disease-specific functionality and are eligible for regulation by the Food and Drug Administration (FDA). In a 2015 guidance document, the FDA has opted to not enforce its regulatory capacity except in specific instances, including when an app "[transforms] a mobile platform into a regulated medical device…"[3] Likewise, Apple guidelines state that apps "that provide diagnoses, treatment advice, or control hardware designed to diagnose or treat medical conditions that do not provide written regulatory approval upon request will be rejected."[4] Despite these guidelines, few of these apps have undergone regulatory review.[5]

Blood pressure (BP) is a physiological measurement commonly obtained as part of a clinical encounter. Elevated BP is a risk factor for myriad diseases, including stroke, myocardial infarction, heart failure, and kidney disease.[6] It is known as the 'silent killer' because of the asymptomatic course that, if left untreated, may result in morbidity or mortality. Early detection and treatment of hypertension is central to evidence-based preventive health care in the United States.[7] Screening for hypertension is typically done with non-invasive BP monitors in the ambulatory setting. These class II FDA devices must be validated prior to approval.[8]

Instant Blood Pressure (IBP; AuraLife, Newport Beach, CA) is an mHealth app that measures BP using just the integrated sensors of a smartphone – no cuff required (

Figure 1A). It was released on the Apple iTunes store on June 5, 2014 and quickly gained popularity (Figure 2). It ranked as a top-50 best-selling for-sale iPhone app for 156 days, which requires ≥950 copies sold per day on average for each of these days at $4.99 per download.[9] It was released on the Google Play store on May 9, 2014 and sold 1,000-5,000 copies.[10] In addition to its commercial success, IBP was celebrated as an innovative app. It won the competitive SoCal Innovation Fund award in March 2015.[11] For unclear reasons, it was removed from the Google Play store on May 9, 2015[12] and the iTunes store on July 30, 2015.[13] Despite its removal, it continues to function for users that have it installed on their phones.

The algorithm by which IBP produces its measurements is proprietary and undisclosed. Before IBP estimates BP, the app asks the user to enter their date of birth, sex, height, and weight (

Figure 1B). After removing any smartphone case, the user is instructed to gently place their right index finger across the illuminated flashlight and camera and place the microphone against the left chest (

Figure 1C). The user interface displays two waveforms during the measurement, the top is labeled “Heart” and the bottom is labeled “Pulse” (

Figure 1D). While it is unclear what the Heart waveform represents, an AuraLife-produced instructional video describes the Pulse waveform as the “pulse activity in your finger.” During the 45 seconds of measurement, the user is coached not to create too much pressure on the index finger as it may cut off circulation.[14] If the measurement is successful, the app will present the user with a systolic BP, diastolic BP, and heart rate (HR).

IBP carries multiple disclaimers, including that it is intended for recreational use only. However, user reviews document use of IBP in managing multiple BP-related conditions including hypertension, postural orthostatic tachycardia syndrome, end-stage renal disease, and post-heart transplant care (Table 1). IBP achieved a 4.0 star rating (out of 5 stars; higher stars indicates a more favorable user experience) on iTunes for its most recent version. Additionally, specific examples of recreational uses of IBP have not been given by the manufacturer on their website. Further, we are unaware of any recreational activity that involves measuring BP. Despite its removal from the iTunes store, IBP continues to function for those who have it installed on their smartphones. Several other ‘me too’ apps with similar functionality and no available validation data (e.g., Blood Pressure Pocket, Quick Blood Pressure Measure and Monitor) are still available for purchase.

As IBP provides functionality equivalent to class II FDA devices, has not been independently validated, and is being used in management of multiple BP-related conditions, we evaluated the accuracy and precision of IBP for BP measurements in adults.

Methods

We developed a protocol based on international sphygmomanometer validation guidelines.[15] This protocol was approved by a Johns Hopkins University School of Medicine institutional review board. Clinicians at 5 ambulatory Hopkins sites (one clinic each in general internal medicine, nephrology, and the ProHealth clinical research unit, and two cardiology clinics) were asked to refer potentially interested adult patients with or without hypertension for enrollment. Individuals could be enrolled either before or after their scheduled appointment. Employees who expressed interest in the study were included as well.

Adults age ≥18 years were included if they expressed interest in the trial. Individuals were excluded if they had an internal device like a pacemaker (per IBP recommendations), had an active arrhythmia (per the automated sphygmomanometer recommendations), or were otherwise unable to use the app (e.g., missing fingers). Per validation guidelines,[15] individuals were excluded if they had change in successive measurements of the reference device >12 mm Hg for systolic and >8 mm Hg for diastolic. Individuals were also dropped if there was an error with the sphygmomanometer. Goal enrollment was 85 individuals.

Prior to BP measurements, participants self-reported sociodemographics, baseline health data (including height, weight, history of hypertension), frequency of BP monitoring, mobile technology use, and mHealth use. They also guessed their current BP. Participants sat quietly for 5 minutes while watching sex-specific manufacturer-provided instructional videos (basic and advanced IBP use for men; basic, advanced part 1, and advanced part 2 for women) on a portable DVD player. Following this, two sequential BPs were taken by each device, separated by 60 seconds. The order for these pairs was randomized.

For IBP measurements, research staff followed manufacturer guidelines using IBP version 1.2.3 on a smartphone (iPhone 5s and 6 running iOS version 8.3, Apple Inc., Cupertino, CA). Staff entered the self-reported date of birth, sex, height, and weight for each participant. Study staff could attempt to obtain a BP result up to three times for each reading in the pair. For standard device measurements, research staff were trained to follow a standard protocol using calibrated, validated automated sphygmomanometers (Omron 907 and 907 XL).[16]

Analysis

Baseline characteristics were compared between those with full sets of IBP measurements and those missing ≥1 measurement. Continuous measurements were compared with two-tailed T-tests and proportions were compared with Chi^2.

Except where specified, all analyses compared each individual IBP measurement to an average of the two standard measurements (sphygmomanometer). We calculated the mean absolute differences between the IBP measurements and standard measurements for systolic BP and diastolic BP, calculated as the mean of the absolute values of the differences between BP measurements by the standard and IBP devices. Mean relative differences were calculated using IBP minus standard. British Hypertension Society (BHS) grading[17] further characterized accuracy. As BP measurements from IBP were not normally distributed by the Shapiro-Wilk test, Spearman ρ was used to assess correlation. Sensitivity and specificity for detection of hypertensive BP were calculated using systolic BP ≥140 and/or diastolic BP ≥90 mmHg, as measured by the standard device. In addition to the analysis described above (Model A), sensitivity analyses for mean absolute differences of BP, mean relative differences of BP, sensitivity and specificity for the detection of hypertensive measurements, and Spearman ρ were calculated using three additional models. Model B compared the first IBP measurement to the first standard measurement. Model C compared the second IBP measurement to the second standard measurement. Model D compared an average of both IBP measurements to an average of both standard measurements.

Precision was assessed using mean absolute differences and mean relative differences for successive measurements by the same device. Mean absolute and relative difference calculations were repeated comparing the user's guess of their own BP versus the standard for BP. These measures (IBP vs. standard and guess vs. standard) were compared using one-tailed T-tests. Mean absolute and relative differences were calculated for IBP versus the standard for HR. Data were visualized with scatterplots and Bland-Altman plots.[18]

To understand the relationship of BP with data entered into the app (date of birth, sex, height, and weight), multiple linear regressions were performed for the first IBP and first standard systolic and diastolic BP measurements. The independent variables were the systolic and diastolic BP measurements from each device. The required data entered by the user (with age substituted for date of birth) and HR were dependent variables. (HR was included because of the degree of accuracy of its measurement by IBP). R^2 was used to characterize the degree of variability in BP from the independent variables. Alternative regression analyses for IBP systolic and diastolic measurements were constructed using forward and backward stepwise selection using interaction terms, squared dependent variables, and splines where appropriate based upon data visualization. The final models were then compared with the original regression model using R^2 and Akaike information criterion (AIC).[19]

All analyses were performed with Stata 13.1 (StataCorp, College Station, TX).

Results

In August and September 2015 we prescreened 105 individuals. Written informed consent was obtained from 101 participants. Data from 16 individuals were discarded because of unavailable cuff sizes, standard device errors, and excessive variation in sequential standard device measurements (Figure 3). The final analysis used the 85 remaining individuals.

Baseline Characteristics

Of 85 participants included in the study, 52% were women, mean (SD) age was 56.6 (16.3) years, and body mass index (BMI) was 27.6 (5.7) kg/m^2; 53% self-reported hypertension, 91% of these reported taking antihypertensive medications (Table 2).

Completion of Measurements

Complete pairs of IBP measurements were obtained from 69 participants and at least one IBP measurement was recorded from 78 participants. Among all IBP pairs, a total of 147 measurements were obtained. The first IBP measurement was missing from 12 participants and the second IBP measurement was missing from 11 participants. The mean number of first and second attempts for IBP measurement were 1.6 (0.8) and 1.5 (0.8). There were a greater proportion of women and a higher mean BMI among those with any missing IBP measurements than those with both IBP pairs (Table 3).

IBP BP Accuracy

The mean absolute difference was 12.4 (10.5) mm Hg for systolic and 10.1 (8.1) mm Hg for diastolic. The mean relative difference (IBP minus standard) was -1.2 (16.2) mm Hg for systolic and 7.1 (10.8) mm Hg for diastolic (Table 4, Figure 4). IBP measurements were ≤5, ≤10, and ≤15 mm Hg of the standard BP measurements 28%, 51%, and 68% of the time for systolic and 31%, 56%, and 81% of the time for diastolic, corresponding with the lowest possible BHS accuracy grade in all categories (Table 5).

Scatterplots of IBP and standard BP demonstrate variation of measurements around the line of identity (solid line) and the regression line of y on x. A direct, positive relationship is evident for both systolic and diastolic BP (Figure 5). Spearman ρ was 0.44 ($P<0.001$) for systolic BP and 0.41 ($P<0.001$) for diastolic BP, indicating a moderate correlation. Hypertensive measurements that were misclassified as non-hypertensive are seen in the bottom right quadrant of each scatterplot. Bland-Altman plots demonstrate a differential pattern across the means, with IBP overestimating low BP and underestimating high BP for both systolic and diastolic measurements (Figure 6).

Sensitivity and specificity of IBP for hypertensive BP were 0.22 and 0.92 (Table 6). These results indicate that of the hypertensive measurements by standard BP, 78% were misclassified as non-hypertensive. Of the non-hypertensive measurements, 92% were classified as non-hypertensive.

Sensitivity Analyses

Mean absolute difference for BP, mean relative difference for BP, sensitivity and specificity for detection of hypertensive BP levels, and Spearman ρ were similar in the four different analysis models (Table 7).

BP Precision

The IBP mean absolute differences for repeated measurements were 3.0 (4.2) mm Hg for systolic BP and 1.2 (1.5) mm Hg for diastolic BP. These measures were 4.6 (3.2) mm Hg and 2.7 (2.1) mm Hg for standard BP (Table 8). Visualization of the individual differences demonstrate less variability between IBP measurements than standard measurements for both systolic and diastolic (Figure 7).

Guess BP Accuracy

The mean absolute difference between the user's guess of their BP and the standard was 9.1 (7.7) mm Hg and 8.3 (7.2) mm Hg for diastolic (Table 8). Scatterplots demonstrate a strong digit preference as well as a positive correlation and variation around the line of fit (Figure 8). Spearman's ρ was strongly correlated for systolic BP (0.70; $P<0.001$) and moderately correlated for diastolic BP (0.53; $P<0.001$). In most analyses, guess performed better than IBP for all but mean relative difference for systolic BP. Bland-Altman plots do not demonstrate a strong differential pattern across the means (Figure 9). Sensitivity and specificity for hypertensive measurements for guessing were 0.67 and 0.90.

IBP HR Accuracy

The mean absolute difference for HR was 2.8 (2.4) BPM and the mean relative difference for HR was 1.1 (3.6) BPM. A scatterplot demonstrates minimal variation around the line of identity, which overlapped with the line of fit (Figure 10). A Bland-Altman plot demonstrates minimal difference across the means (Figure 11). Spearman's ρ was very strongly correlated (0.95; $P<0.001$).

Regression Analysis

Regressing the systolic and diastolic results for each device onto the user profile inputs and HR resulted in statistical significance for weight and age for IBP systolic and IBP diastolic BP, age for standard systolic BP, and weight and HR for standard diastolic BP. The R^2, or percentage of variance explained by the model, were 0.675 and 0.847 for IBP systolic and diastolic BP regressions and 0.115 and 0.198 for standard systolic and diastolic BP regressions (Table 10).

Based upon scatterplots relating IBP systolic and diastolic BP to age, height, weight, and HR (Figure 12), a spline term was generated at age 45. Models generated through forward and backward stepwise selections were similar to the original regression in their R^2 and AIC (Table 11).

Discussion

In this independent validation study of the IBP app, we documented that this app performed poorly in measuring BP. It achieved the lowest possible BHS accuracy grade and misclassified approximately four-fifths (78%) of hypertensive measurements as non-hypertensive. Ambulatory patients in clinical settings guessed their BP with greater accuracy than IBP for three of four measures in this study. IBP accurately measured HR.

IBP had a similar precision to the reference device for measurement of BP and varied little between subsequent BP measurements. The mean relative difference was close to zero for systolic BP and within 10 mm Hg for diastolic BP. A high R^2 from the regression models suggest that IBP might estimate BP from age, sex, height, weight, and HR. These findings suggest that IBP's BP estimates may be based on algorithms that incorporate data from population estimations of BP from demographic data, rather than direct measurements of BP alone. That it is unable to produce measurements more frequently in women with greater BMI suggests that breast tissue may impede the recording of the heart beat by the microphone. This in turn may prevent the population-derived equation from functioning as a HR may not be calculated. The 15-32% remaining variability for the estimated BP may be from an algorithm relating audio sampling of the chest and video sampling of the fingertip. It is not clear from our data what this algorithm may be.

Strengths of the study include design based on international guidelines, diverse participants, and a standardized protocol emphasizing best practices for sphygmomanometer use and manufacturer practices for IBP use. Limitations include a small distribution of diastolic BP measurements and no assessment of the Android IBP app.

Our study has both clinical and public health relevance. While IBP recently became unavailable for unclear reasons,[20] it was purchased by >148,000 users and is installed on a vast number of iPhones; further, several 'me-too' apps are still available. Hence, we remain concerned that individuals may use these apps to assess their BP and titrate therapy. Second, our results might have regulatory implications. That an app with functionality identical to FDA-regulated sphygmomanometers can top an app store's sales ranks without independent validation means that processes are not in place to ensure rigorous testing of mHealth apps prior to release to consumers. As there are >165,000 mHealth apps available, there is an urgent need for development and enforcement of regulatory standards.

Tables

*Table 1- Selected ratings and from iTunes for IBP version 1.2.3**

Date of review	Review title, user name, star rating, and review narrative
6/7/2015	"Emergency room nurse" by Scot21t (5 stars) Works for me with iPhone 6+ and with the current case I have on. I don't know the formula that is used to determine the blood pressure but for me is no different than an automatic machine taking the pressure a few times and being a few points off. I take medicine for high blood pressure and works for me.
6/5/2015	"Life Saver!!" by Berduh (5 stars) I recently have and an increase in my blood pressure and now needs to be monitor. So this app has been a life saver for me and now I'm able to check my pressure whenever I need to!!
7/13/2015	"As a Dialysis patient...." by God Iz Raw (4 stars) I think this is very good to have for people who suffer with high blood pressure, Dialysis patients, stroke patients and maybe even other patients who need to check their blood pressure anywhere.
5/11/2015	"Works great and is easy to use" by OhMia83 (5 stars) I love this app!! It is worth every penny. I have POTS and am taking an antihypertensive medication and I have to monitor by B/P to make sure I don't get hypotensive. This is so much easier to use than my cuff and is just as accurate. I even use my phone with my case on without problems. I have only had a time or two that it couldn't get a reading. This app is just the first step to having multiple apps that can monitor our vital signs and more!
5/23/2015	"I am a Heart Transplant Recipient of 02/04/2014" by Us1952 (5 stars) I like it... Looking forward to being able to store the test results!! Note: I am a Heart Transplant recipient this year 02/04/2015 Saint Luke's Mid America Transplant Institute, Kansas City, Mo. I take daily BP with a BP Cuff supplied by the Transplant Center. I have also been using this BP App. as a comparison. It is surprisingly very close to my readings. Just a couple of points off +/- !!! I am also a Biomedical Engineer/IT, Application Consultant for Cerner Corp. I am truly impressed with your BP application!!!
7/3/2015	"Highly recommend, surprised at accuracy" by Last Hope MN (5 stars) I highly recommend this app. It is quite accurate. I believe only a trained person could reach increased accuracy with a blood pressure cuff, on the left arm, and a stethoscope. For first aid situations, especially in isolated, outdoor situations, I find this app very useful, especially for a person going into or already in shock (continual, falling blood pressure). Severe shock can be fatal. With the information, I can determine if I should activate the EPIRB - do I have a life threatening condition, ex. severe shock. And I can measure a person's blood pressure many times during a few hours. This cannot be done with a cuff (blood vessels may spasm after repeated measurements). Several years ago, before iPhones existed, I looked for a finger tip blood pressure measurement. I could only find one model, sold only in Japan, and I was unable to purchase it. Now, I finally have a method. Thank to the developers.
6/11/2015	"Life Saver" by Cash Tracker (5 stars) What a great app. Gives me the opportunity to check when I forget my meds. Let's me know when I am in trouble.

6/7/2015	“Impressive “ by DrawingOne (5 stars) What a handy app when I want to check my BP and my cuff would be too weird to have nearby. As my meds are being adjusted I like to check a few times and, obviously, don't want to walk around with my cuff in my purse. As others have said, this app comes within a few points of my manual sphygmomanometer. The usual instructions to sit quietly for 5 min (really) before doing a measurement applies to the app, too. Easy to find something to do for 5 min when your phone is in your hand. Terrific technology that will surprise your docs, too!
5/23/2015	“Great app” by Nott317 (5 stars) Had surgery recently and have to monitor my bp frequently. App works great and kicks out the same measurements as at my docs office and at my professional style home kits. My doc is recommending the app to other patients after tracking my progress. Pretty awesome!
6/20/2015	“Great” by B-den Cruz (5 stars) Definitely worth the download. I seem to have "white coat syndrome" so using this to take a measurement on my own is really helpful.
6/29/2015	“Excellent and practical!!!!” by Luigi5050 (5 stars) Easy to use, can take pressure anytime without arm or wrist gadgets and purely with the phone! To cap it all, this app is much more accurate and reliable than the clunky Omron machine I recently bought (and now returned!).

*Downloaded from MixRank.com on January 11, 2016. The review title is presented in quotations followed by the user name. Star ratings are out of 5 with a higher rating indicating a more favorable user impression.

Table 2 - Baseline characteristics of the 85 participants

	Mean (SD) or %	**Range**
Age, y	56.6 (16.2)	18.9-81.2
Height, cm	168.2 (10.0)	147.3-188.0
Weight, kg	78.9 (19.2)	44.0-140.2
BMI, kg/m^2	27.6 (5.7)	17.5-45.3
Arm circumference, cm	31.3 (5.1)	21.0-52.0
Sociodemographics		
Male sex, %	48.2	
Race and ethnicity		
White race, %	61.2	
Black race, %	28.2	
Asian race, %	9.4	
Other race, %	1.2	
Hispanic ethnicity, %	4.8	
BP		
Systolic, mm Hg*	126.1 (17.3)	92-170
Diastolic, mm Hg*	69.8 (11.4)	32-100
HR, BPM	67.7 (11.8)	45-94
Hypertensive BP measurement, %**	21.2	
Number of attempts for first IBP measurement	1.6 (0.79)	1-3
Number of attempts for second IBP measurement***	1.5 (0.84)	1-5
Prior diagnosis of hypertension, %	52.9	
On hypertensive medications, % of those with prior diagnosis of hypertension	91.1	
Use of technology		
Owns a BP monitor, %	64.7	
Checks BP monthly or more, %	49.4	
Owns a mobile device, %	83.5	
Owns an mHealth app, % of those owning a mobile device	43.7	
Non-patients, %******	22.4	
Patients enrolled after completion of scheduled appointment, %	71.2	

*Average of both standard measurements.
**As defined by standard BP ≥140 or diastolic BP ≥90 mmHg.
***One participant requested continued attempts until a second IBP measurement was obtained. It was obtained on the fifth try and was included in this analysis.
****All non-patients were employees who expressed interest in participating in the trial.

Table 3 - Comparison of participants with full sets of BP measurements or missing ≥1 measurement, mean (SD) or percentage

	All IBP measurements (n=69)	**Missing ≥1 IBP measurement (n=16)**	**P-value***
Age, y	55.9 (16.7)	59.6 (14.1)	0.43
Height, cm	168.8 (10.0)	165.6 (10.3)	0.55
Weight, kg	77.1 (19.0)	86.6 (18.9)	0.08
BMI, kg/m^2	26.9 (5.5)	30.9 (5.2)	**0.01**
Arm circumference, cm	30.8 (4.5)	34.1 (7.4)	**0.05**
Sociodemographics			
Male sex, %	53.6	25.0	**0.04**
Race and ethnicity			
White race, %	62.3	56.3	0.65
Black race, %	24.6	43.8	0.13
Asian race, %	11.6	0	0.15
Other race, %	1.4	0	0.62
Hispanic ethnicity, %	5.9	0	0.32
BP			
Systolic, mm Hg**	126.4 (17.6)	124.6 (17.1)	0.70
Diastolic, mm Hg**	70.1 (11.6)	68.4 (10.4)	0.59
Hypertensive BP measurement, %***	20.3	25.0	0.68
HR, BPM**	67.6 (11.4)	68.2 (13.9)	0.84
Number of attempts for first IBP measurement	1.30 (0.6)	2.6 (0.7)	**<0.01**
Number of attempts for second IBP measurement	1.2 (0.5)	2.8 (0.9)	**<0.01**
Prior diagnosis of hypertension, %	55.1	43.8	0.41
On hypertensive medications, % of those with prior diagnosis of hypertension	92.1	85.7	0.58
Use of technology			
Owns a BP monitor, %	63.8	68.8	0.71
Checks BP monthly or more, %	52.2	37.5	0.29
Owns a mobile device, %	82.6	87.5	0.64
Owns an mHealth app, % of those owning a mobile device	47.4	28.6	0.20
Non-patients, %****	23.2	18.8	0.20
Patients enrolled after completion of scheduled appointment, %	77.3	46.2	**0.02**

*By Chi^2 for proportions and T-test (two-tailed) for continuous variables.
**Average of both standard measurements.
***As defined by standard BP ≥140 or diastolic BP ≥90 mmHg.
****All non-patients were employees who expressed interest in participating in the trial.

Table 4 - Mean difference of IBP minus standard BP, mm Hg (SD),n=147 IBP measurements among 85 pairs

	Absolute	Relative
Systolic BP	12.4 (10.5)	-1.2 (16.2)
Diastolic BP	10.1 (8.1)	7.1 (10.8)

*Table 5 - BHS Accuracy Grade**

Grade	≤5 mm Hg	≤10 mm Hg	≤15 mm Hg
Cumulative percentages of readings			
A	**≥60%**	**≥85%**	**≥95%**
B	**50% to <60%**	**75% to <85%**	**90% to <95%**
C	**40% to <50%**	**65% to <75%**	**85% to <90%**
D	**<40%**	**<65%**	**<85%**
IBP percentage in each range (grade)			
Systolic BP	28% (D)	51% (D)	68% (D)
Diastolic BP	31% (D)	56% (D)	81% (D)

*Percentage of IBP readings differing from the standard device by each range category.

*Table 6 - 2x2 table, sensitivity and specificity for hypertensive measurements**

		Standard		
		Hypertensive	**Non-hypertensive**	**Total**
IBP	**Hypertensive**	7	9	16
	Non-hypertensive	24	107	131
	Total	31	116	147

Sensitivity: 0.225
Specificity: 0.922
Positive predictive value: 0.438
Negative predictive value: 0.817
*Defined as systolic BP ≥140 mm Hg and/or diastolic BP ≥90 mm Hg.

*Table 7 - Sensitivity analyses**

	Model A	Model B	Model C	Model D
Mean difference**				
Absolute				
Systolic BP	12.4 (10.5)	12.5 (10.5)	13.1 (10.5)	12.4 (10.3)
Diastolic BP	10.1 (8.0)	10.3 (8.3)	10.1 (7.9)	10.3 (8.0)
Relative				
Systolic BP	-1.2 (16.2)	-1.5 (16.4)	-1.1 (16.8)	-1.0 (16.1)
Diastolic BP	7.1 (10.8)	7.1 (11.2)	7.1 (10.7)	7.4 (10.8)
Detection of hypertensive BP				
Sensitivity	0.22	0.21	0.19	0.18
Specificity	0.92	0.92	0.91	0.97
Spearman ρ***				
Systolic	0.44 (<0.001)	0.49 (<0.001)	0.40 (<0.001)	0.43 (<0.001)
Diastolic	0.41 (<0.001)	0.39 (<0.001)	0.42 (<0.001)	0.42 (<0.001)

*Model A is the model presented in all other analyses, comparison of the individual IBP measurements to an average of both standard measurements. Model B is a comparison of the first IBP measurement to the first standard measurement. Model C is a comparison of the second IBP measurement to the second standard measurement. Model D is a comparison of the average of both IBP measurements to the average of both standard measurements. In model D, if there was only one measurement recorded for IBP, the lone IBP measurement was compared to an average of both standard measurements. Hypertensive measurements are defined as systolic BP ≥140 mm Hg and/or diastolic BP ≥90 mm Hg.
**Presented as mm Hg (SD). The relative mean difference is IBP minus standard BP.
***Presented as ρ (p-value)

*Table 8 – Precision of IBP and standard for BP measurements, mean differences of subsequent measurements, mm Hg (SD)**

	IBP		**Standard**	
	Absolute	**Relative**	**Absolute**	**Relative**
Systolic BP	3.0 (4.2)	-0.2 (5.2)	4.6 (3.2)	<0.1 (5.6)
Diastolic BP	1.2 (1.5)	-0.1 (1.9)	2.7 (2.1)	-0.2 (3.4)

*Calculated as the first reading minus the second reading for each device.

Table 9 - Mean difference of BP, participant's guess minus standard, mm Hg (SD)

	Guess vs. standard	**IBP vs. standard**	**P-value***
Absolute			
Systolic BP	9.1 (7.7)	12.4 (10.5)	0.005
Diastolic BP	8.3 (7.2)	10.1 (8.1)	0.042
Relative			
Systolic BP	-0.3 (11.9)	-1.2 (16.2)	0.672
Diastolic BP	4.4 (10.1)	7.1 (10.8)	0.031

*T-test, one-tailed using Model A. As the IBP measurements were obtained in pairs, they were not truly independent. This was repeated using Model D (Table 7). The P-values were similar between models.

Table 10 - *Regression analysis**

Equation: BP = β*male sex + β*height + β*weight + β*age + β*HR + constant

	BP	Male sex	Height (in)	Weight (lb)	Age (y)	HR (BPM)**	Constant	R^2
		Beta coefficients						
IBP	Systolic	-0.24	0.59	0.17***	0.24***	0.02	41.19	0.67
	Diastolic	-0.50	0.14	0.10***	-0.11***	0.03	55.28	0.85
Standard	Systolic	-0.52	0.60	0.04	0.33***	0.01	59.54	0.12
	Diastolic	-0.10	0.08	0.07***	0.05	0.31**	28.28	0.20

*The regression is a pairing of the first measure from each device.
**HR is taken from the same device's reported measurement.
***P<0.05.

Table 11 - Forward and backward stepwise selection of regression models

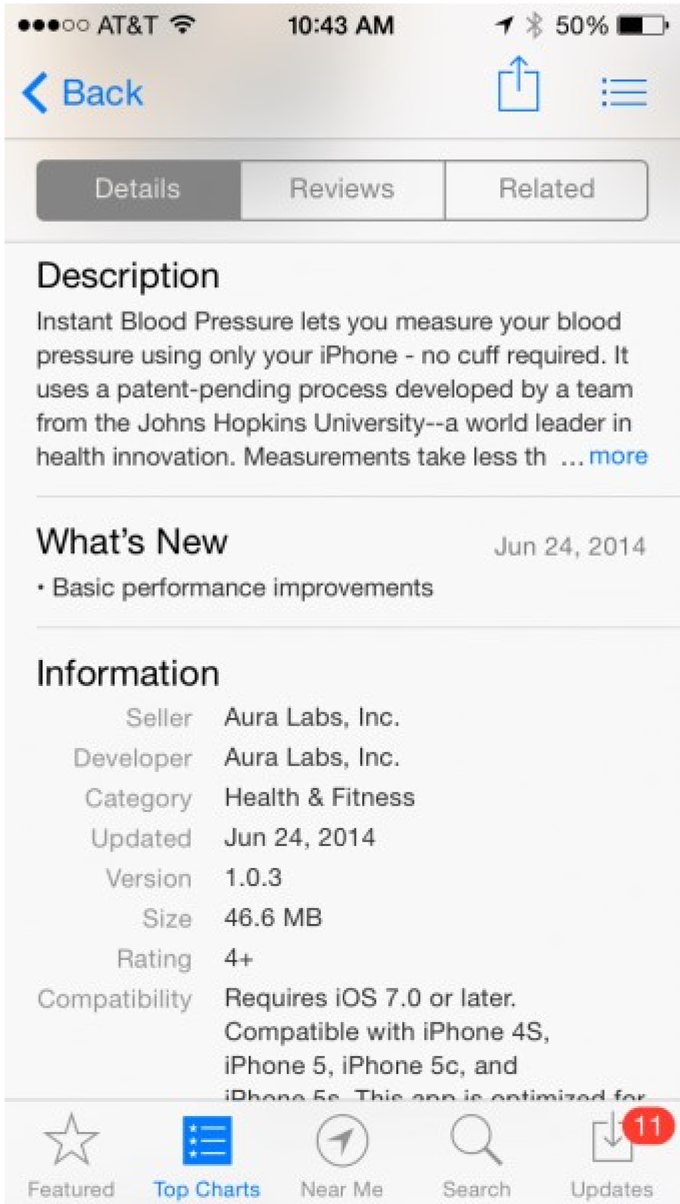
Model	**Variables included in the final model***	**R^2**	**AIC****
IBP systolic BP			
Original regression***	Male sex, height, weight, age, HR	0.67	486.75
Stepwise selection type****			
Forward	Height*weight, age^2	0.68	479.53
Backward	Age spline ≥45*****, height*age, weight, weight*age, $weight^2$	0.71	476.55
IBP diastolic BP			
Original regression	Male sex, height, weight, age, HR	0.85	311.34
Stepwise selection type			
Forward	Height*age, height*weight	0.84	307.04
Backward	Male sex, weight*age, weight, sex*height	0.86	305.37

*Variables available for inclusion in model building included those in Table 10, interaction terms between Male sex, height, weight, age, and HR, a spline at age 45, and squared terms for height, weight, age, and HR.
**AIC is Akaike's Information Criterion and can be used to compare the relative quality of regression models, with a lower AIC indicating a higher quality model.[19]
***This is the regression analysis presented in Table 10
****Stepwise selection used $P<0.05$ as the threshold for variable inclusion
*****This spline was added based upon visualization of data with BP related to age (Figure 12). It represents the difference in BP between those younger than 45 and those age 45 or older.

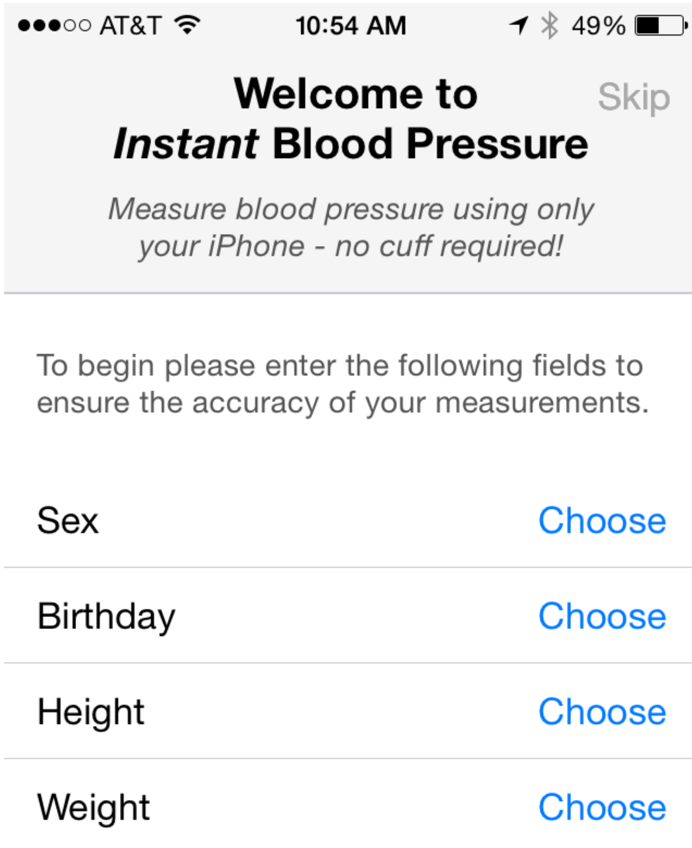
Figures

Figure 1 – IBP Marketing Materials and Screenshots

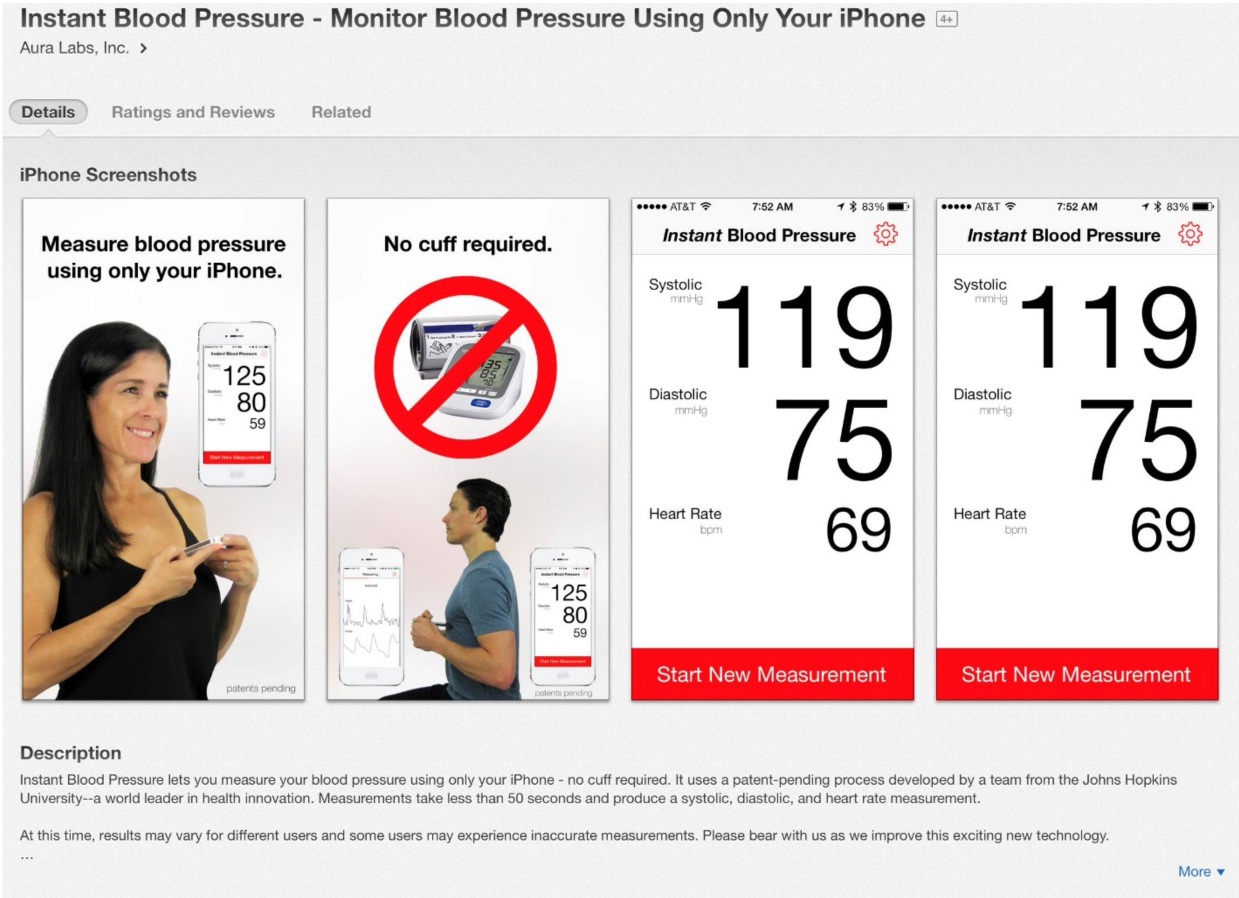
A) 2014 IBP App Description



B) 2014 IBP Screenshot of User Profile entry



C) 2014 iTunes Listing



D) 2014 IBP User Interface Screenshot

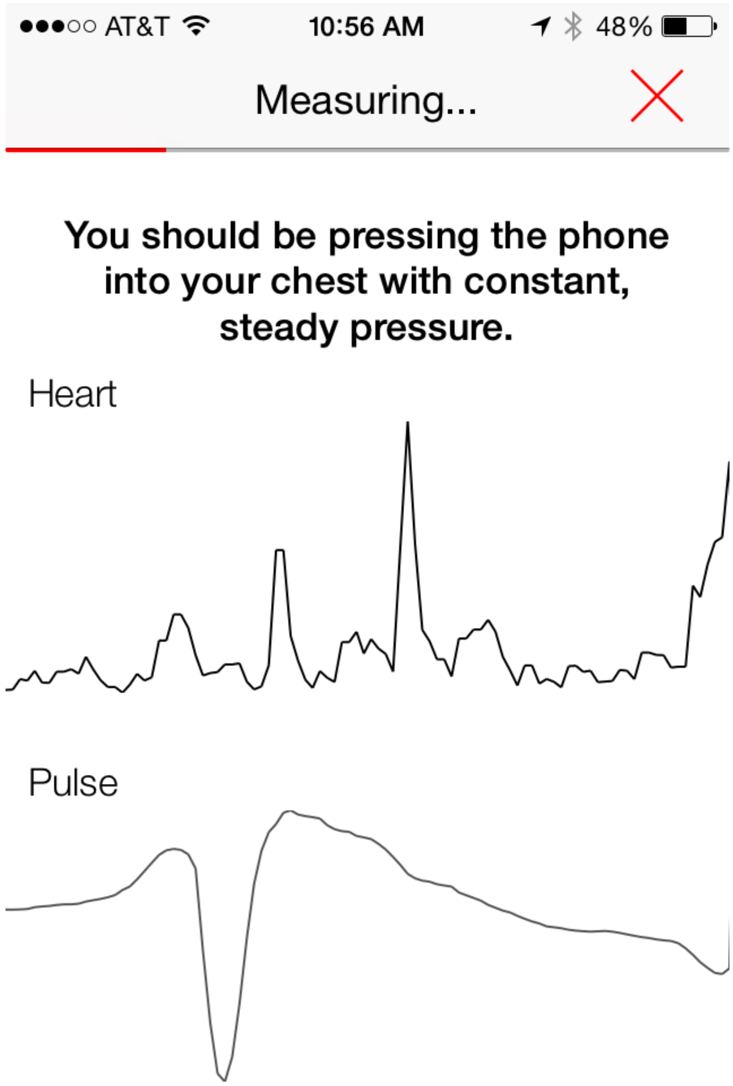
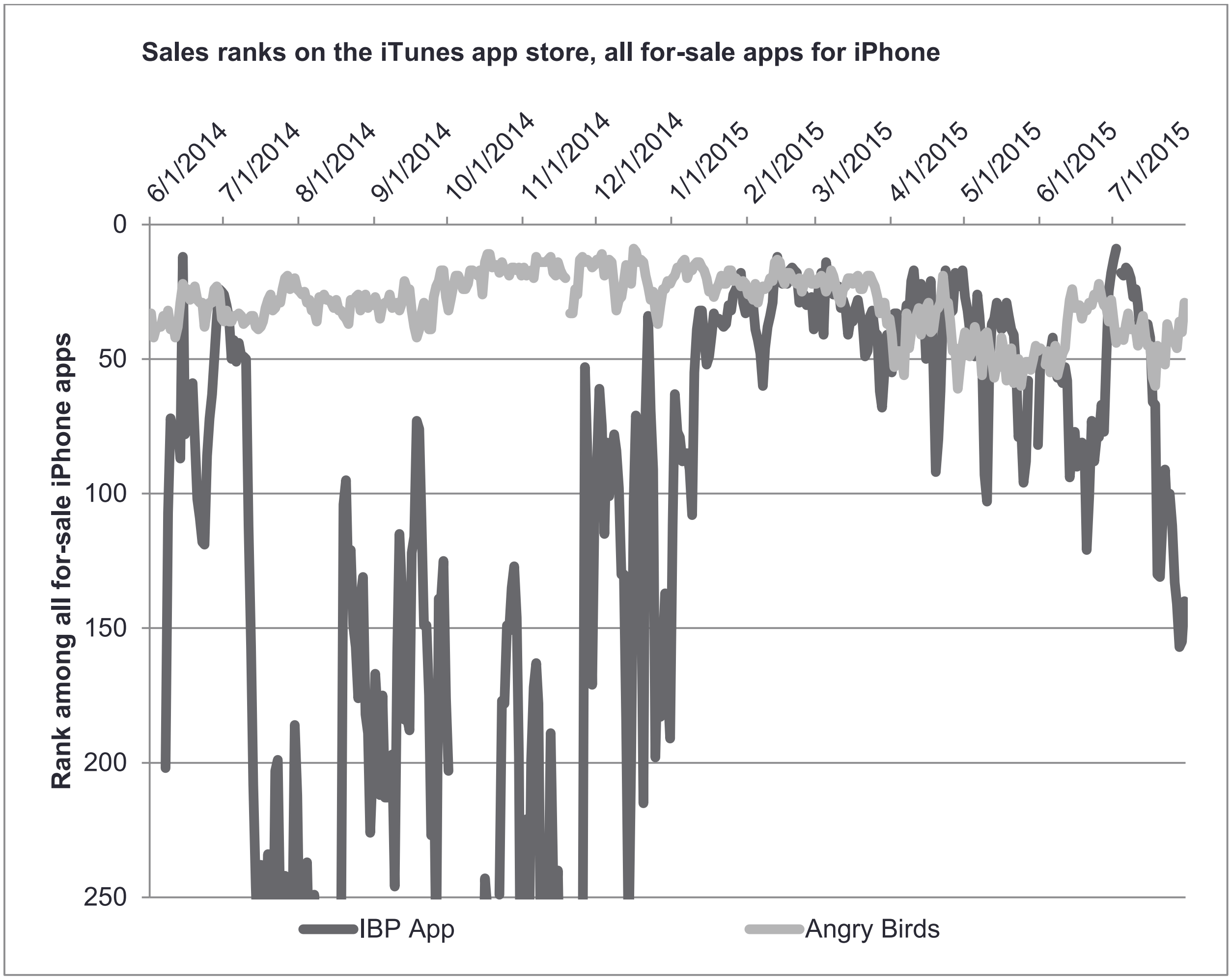


Figure 1 images were downloaded from http://www.imedicalapps.com/2014/07/iphone-health-app-patient-harm/ on 2016-03-11. These were originally published on 2014-07-14.

*Figure 2 - Rank on Apple iTunes Store**



*Angry Birds is a popular smartphone video game. Sales rank history was downloaded from AppFigures.com.

Figure 3 - CONSORT Flow Diagram

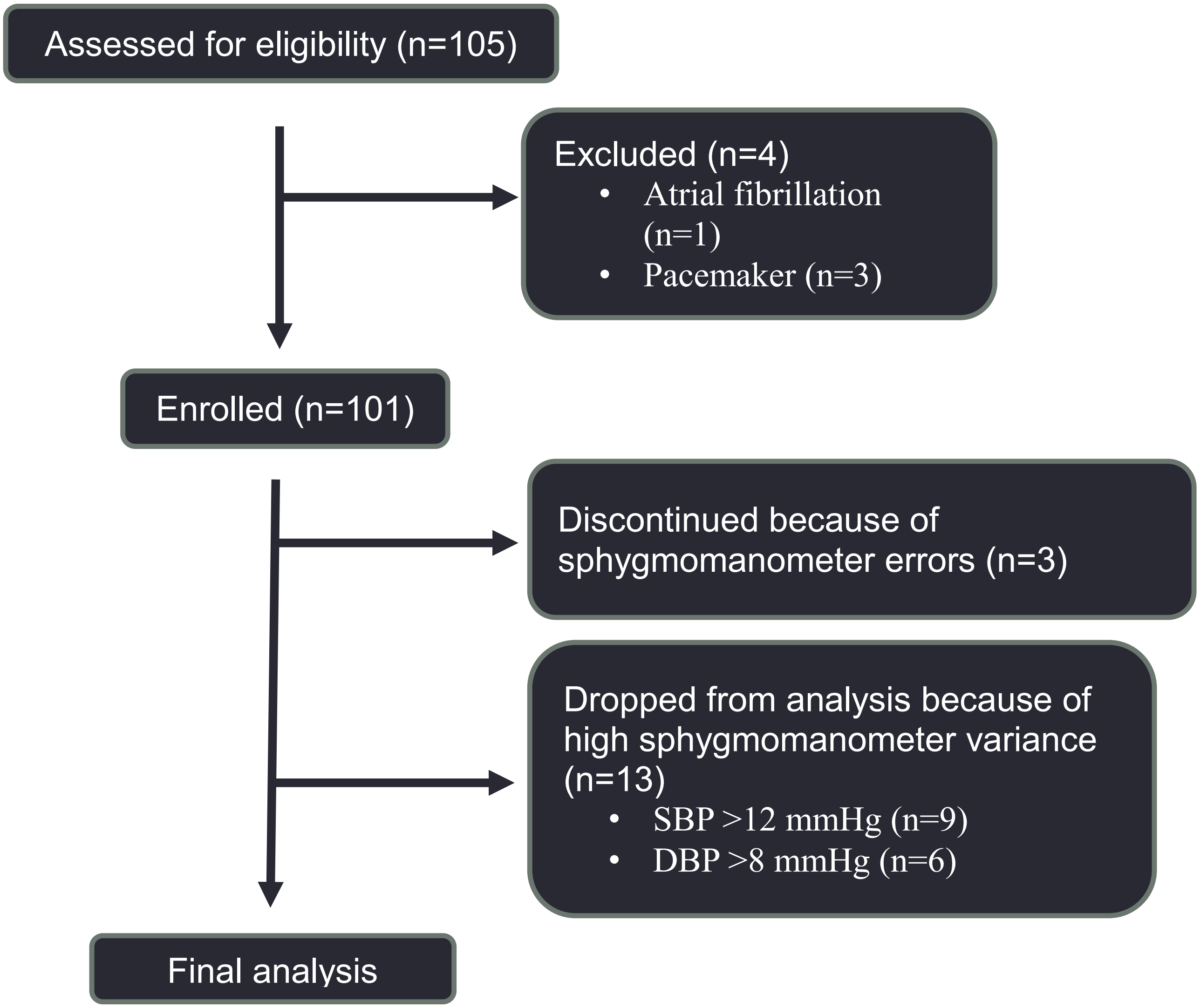
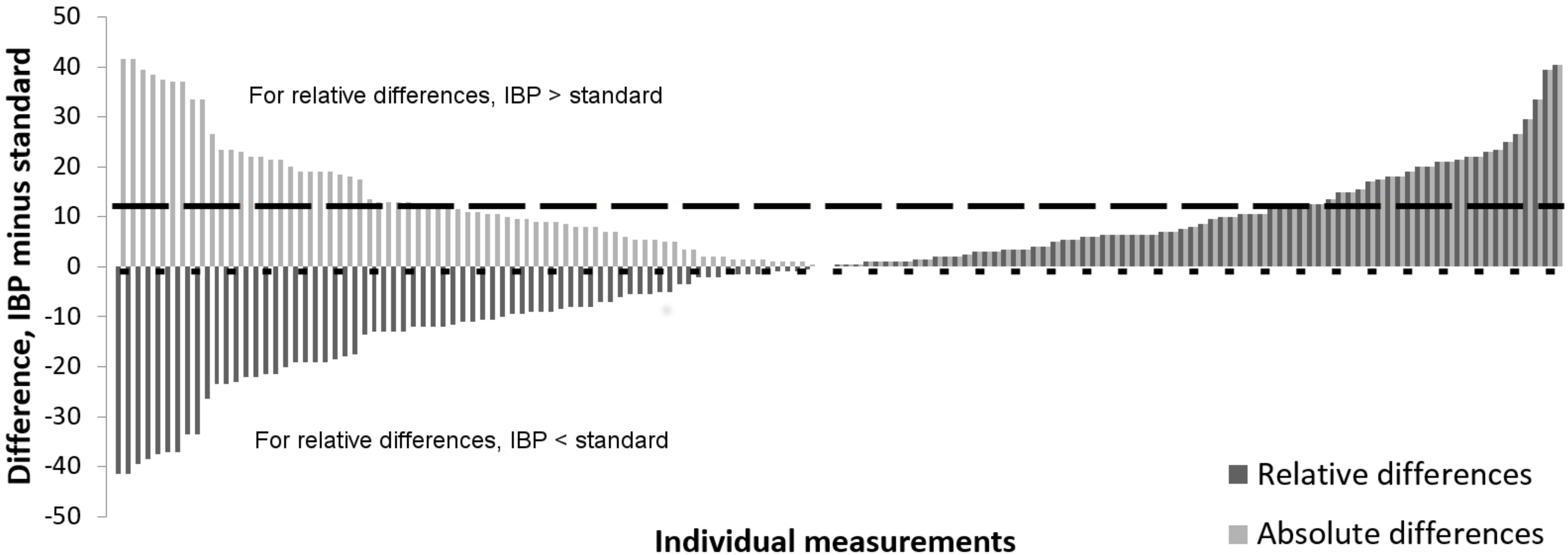
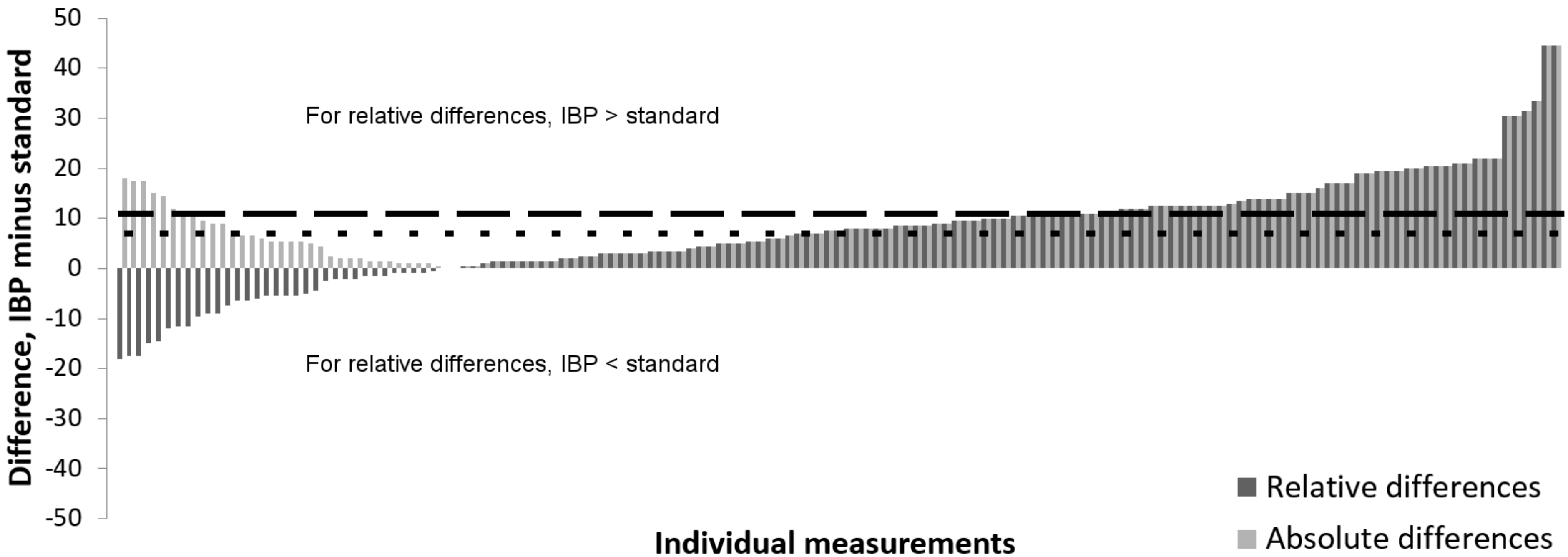


Figure 4 - Differences between IBP and Systolic BP Measurements, ordered by magnitude of the relative differences

A) Systolic*

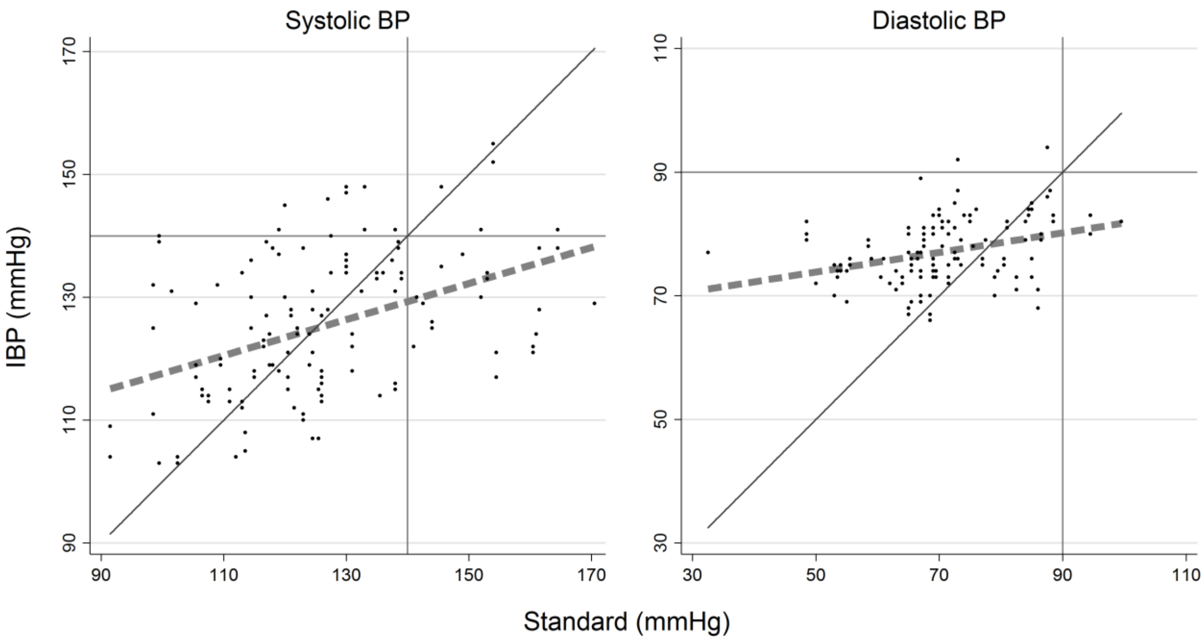


B) Diastolic



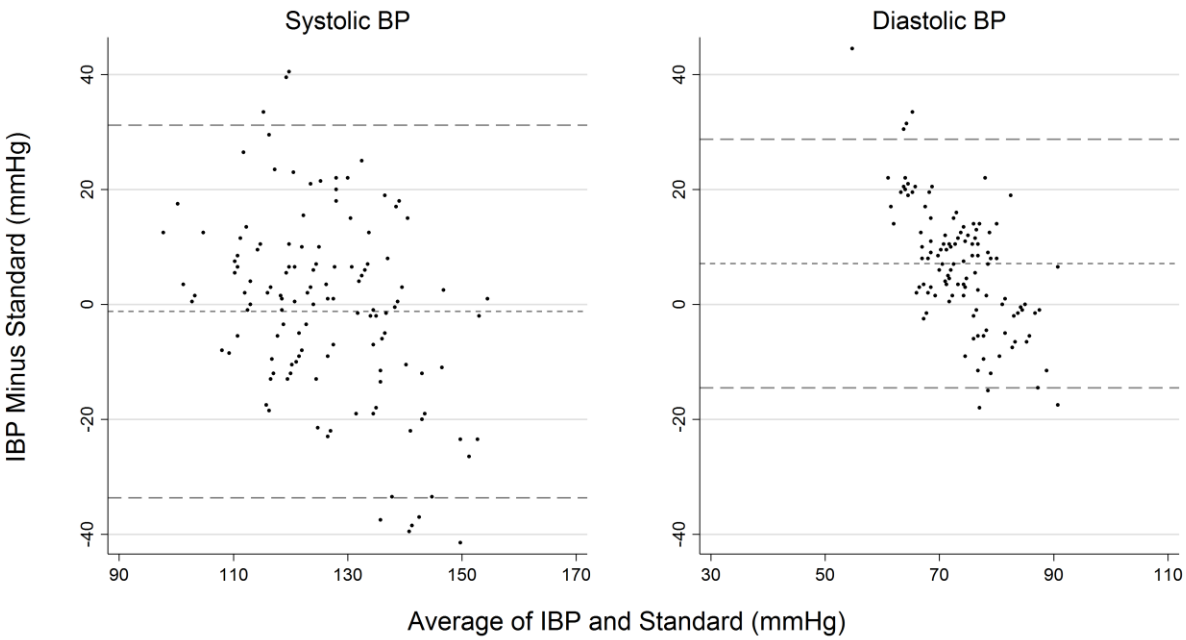
*The relative differences are in dark grey, absolute differences are in light grey. The dashed lines are the mean absolute differences. The dotted lines are the mean relative differences.

*Figure 5 - Scatterplots, IBP vs. Standard for BP**



*The diagonal black solid lines are lines of unity. The vertical and horizontal black solid lines are cutoffs for hypertensive measurements. The grey dotted line is the line of fit.

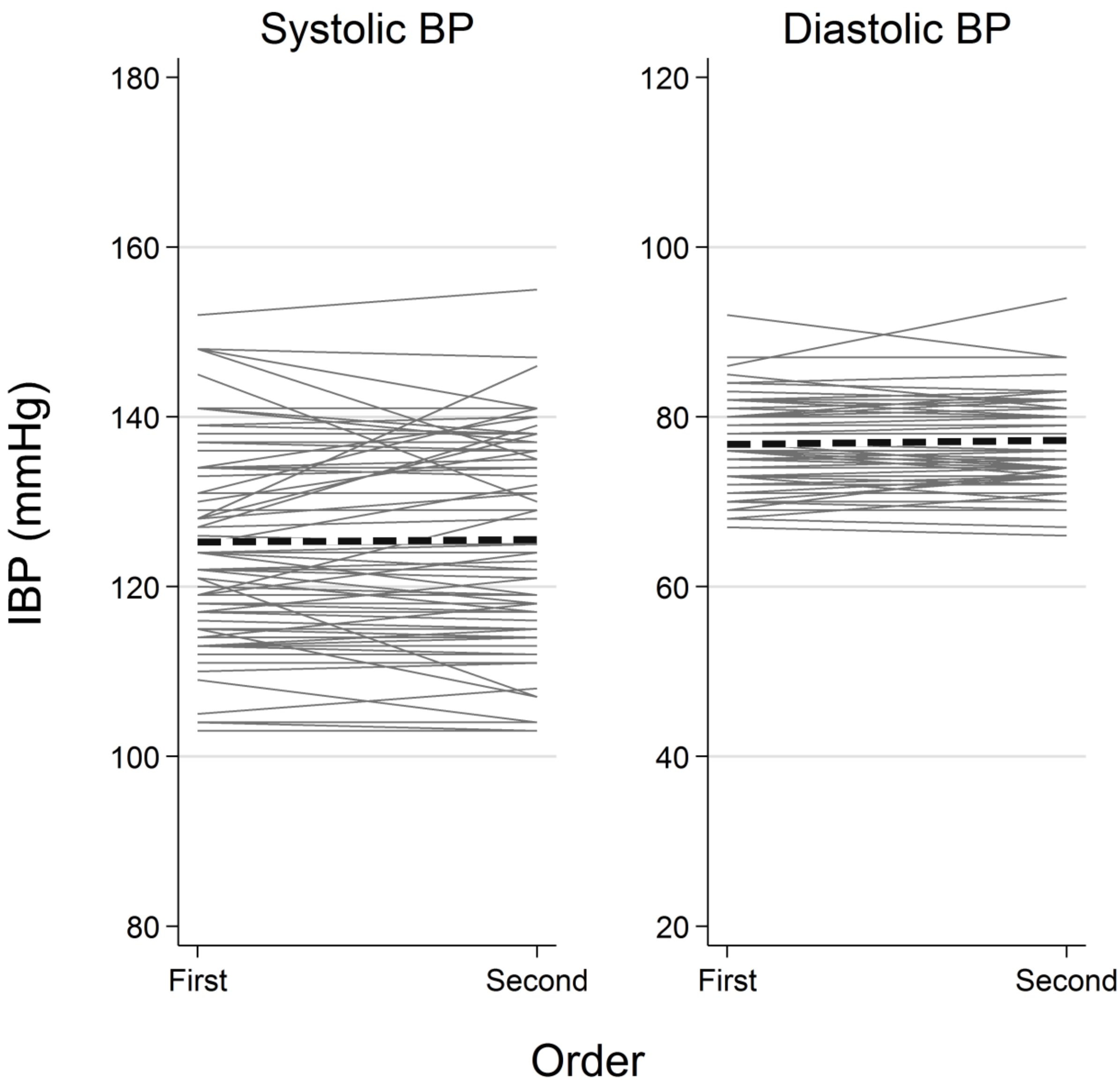
*Figure 6 - Bland-Altman Plots, IBP and Standard for BP**



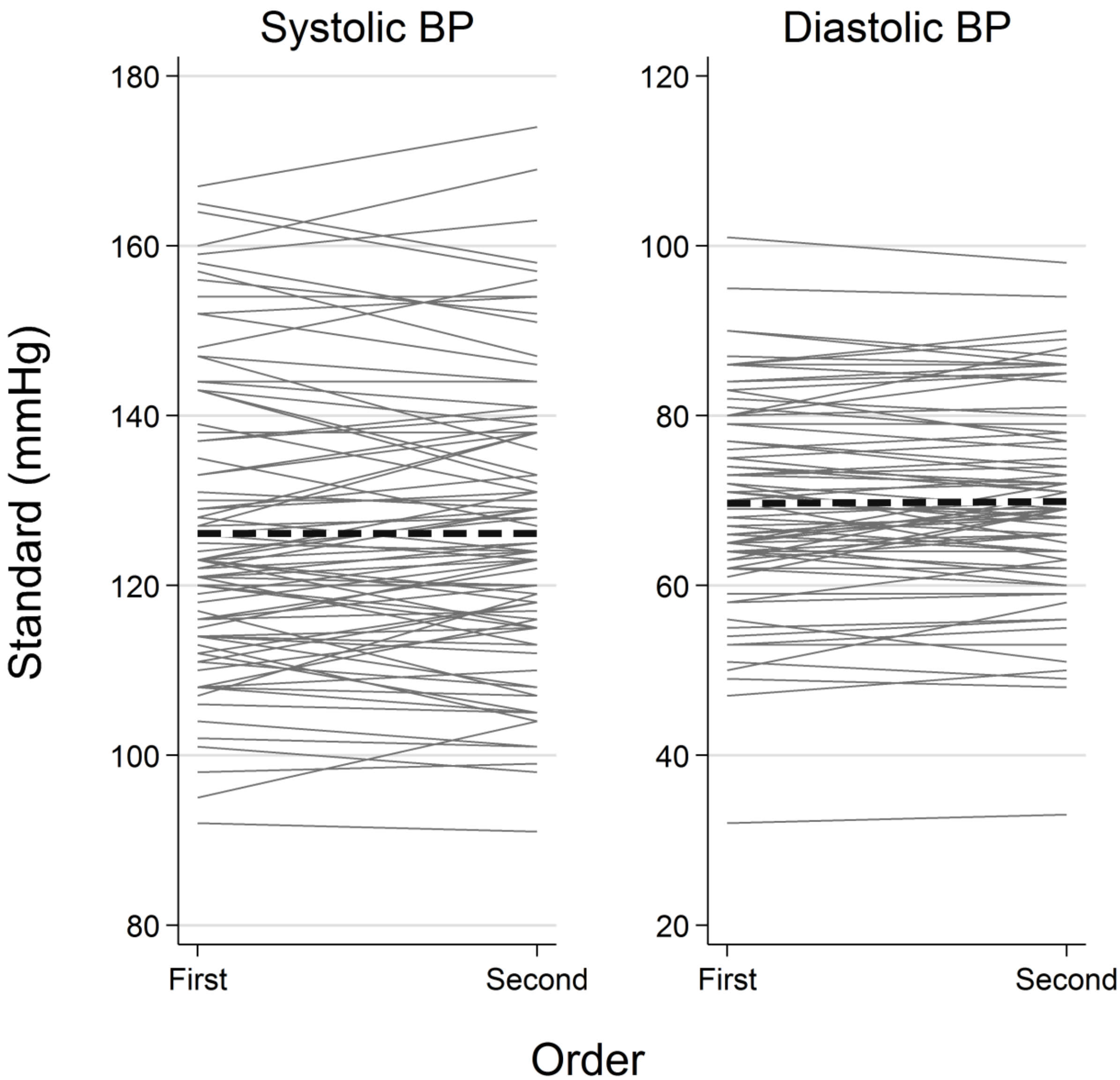
*The short dashed lines are the mean relative differences. The long dashed lines are ±2 SD.

*Figure 7 - Change in Successive BP Measurements**

A) IBP

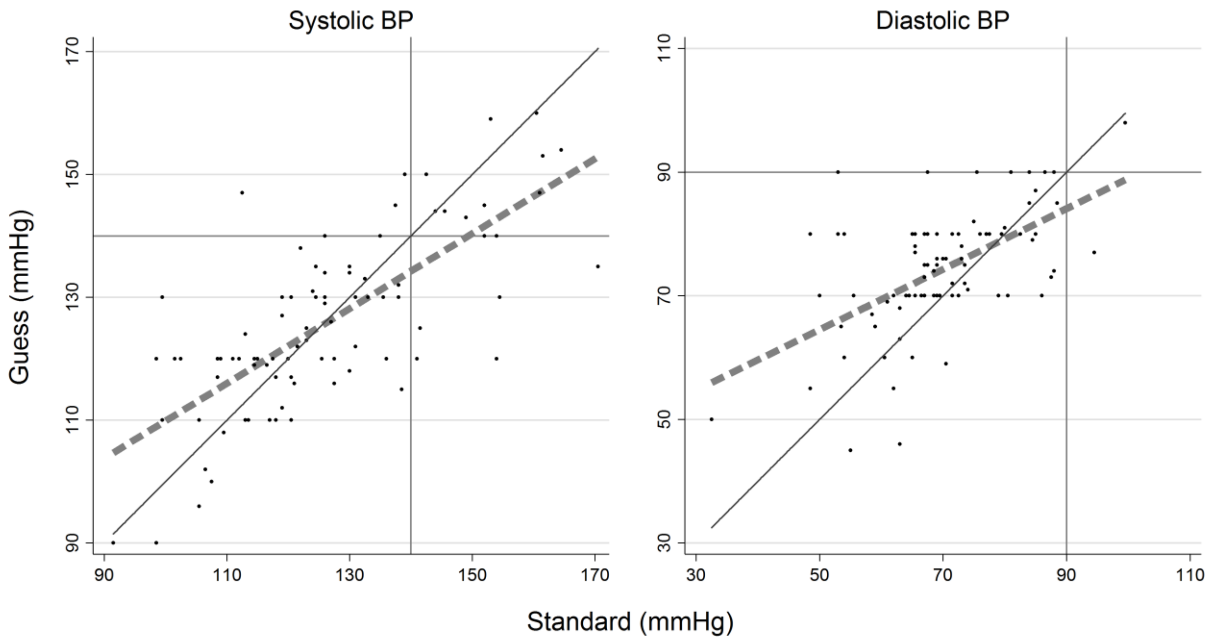


B) Standard



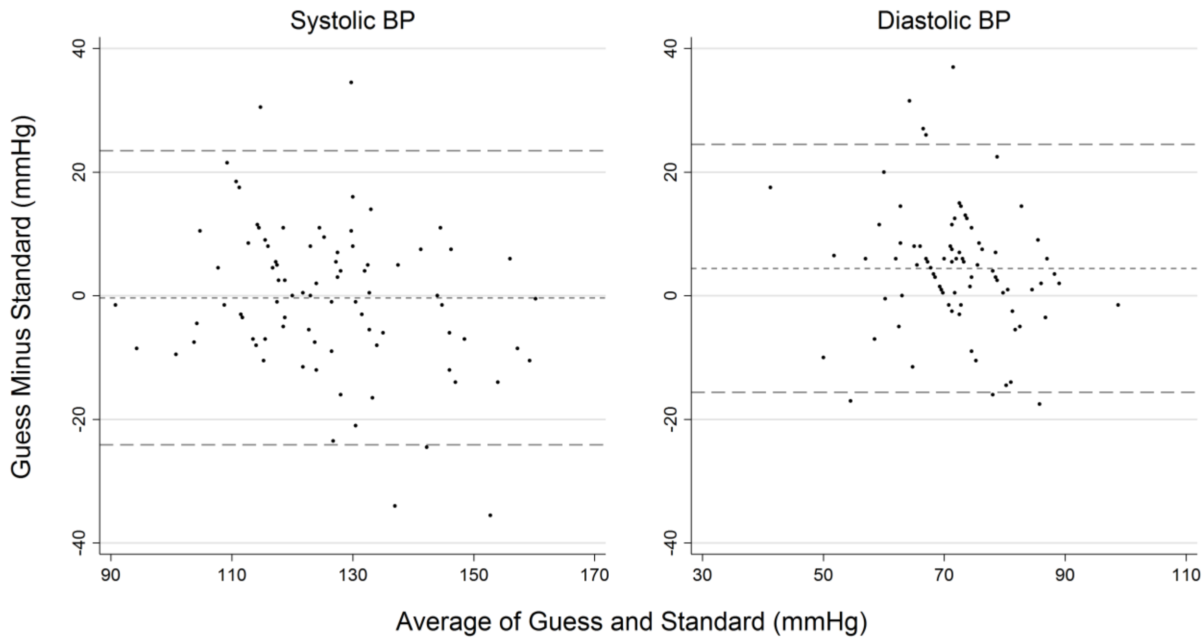
*The grey solid lines are the change in subsequent measures between devices. The black dashed lines are the mean relative differences between measurements.

*Figure 8 - Scatterplots, Guess vs. Standard for BP**



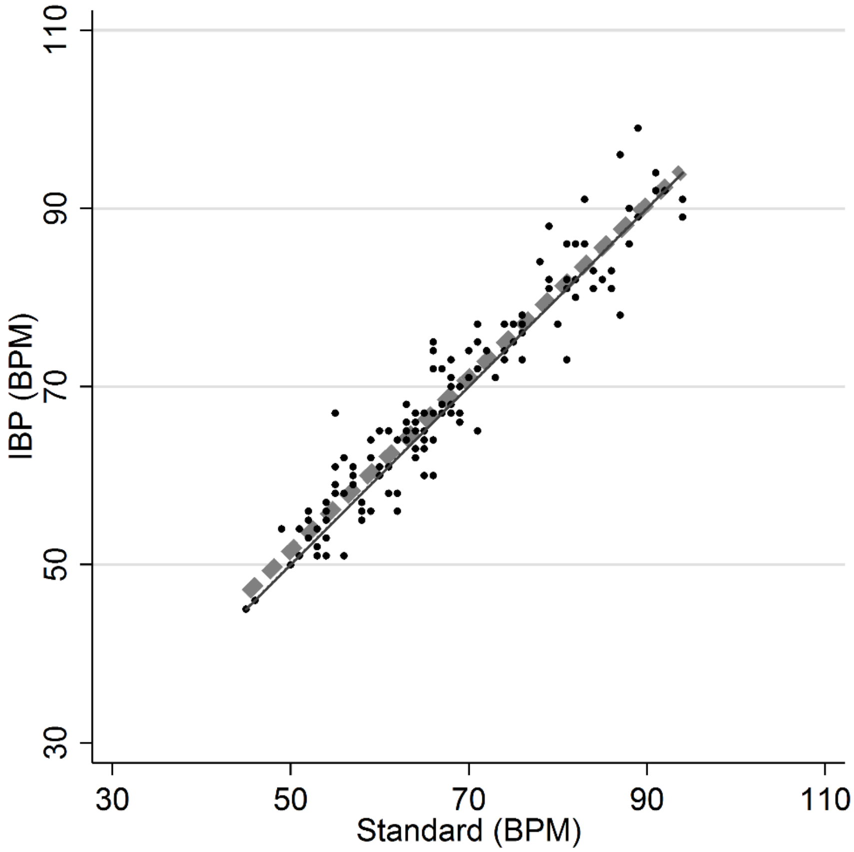
*The diagonal black solid lines are lines of unity. The vertical and horizontal black solid lines are cutoffs for hypertensive measurements. The grey dotted line is the line of fit.

*Figure 9 - Bland-Altman Plots, Guess and Standard for BP**



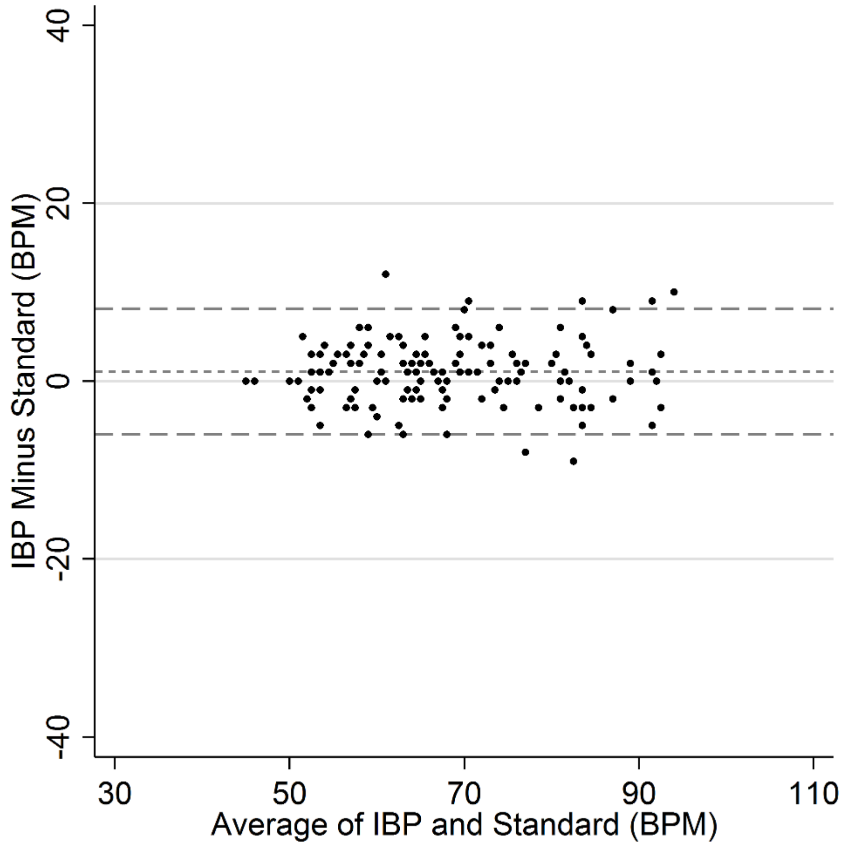
*The short dashed lines are the mean relative differences. The long dashed lines are ±2 SD.

*Figure 10 - Scatterplot, IBP vs. Standard for HR**



*The diagonal black solid line is the line of unity. The grey dotted line is the line of fit.

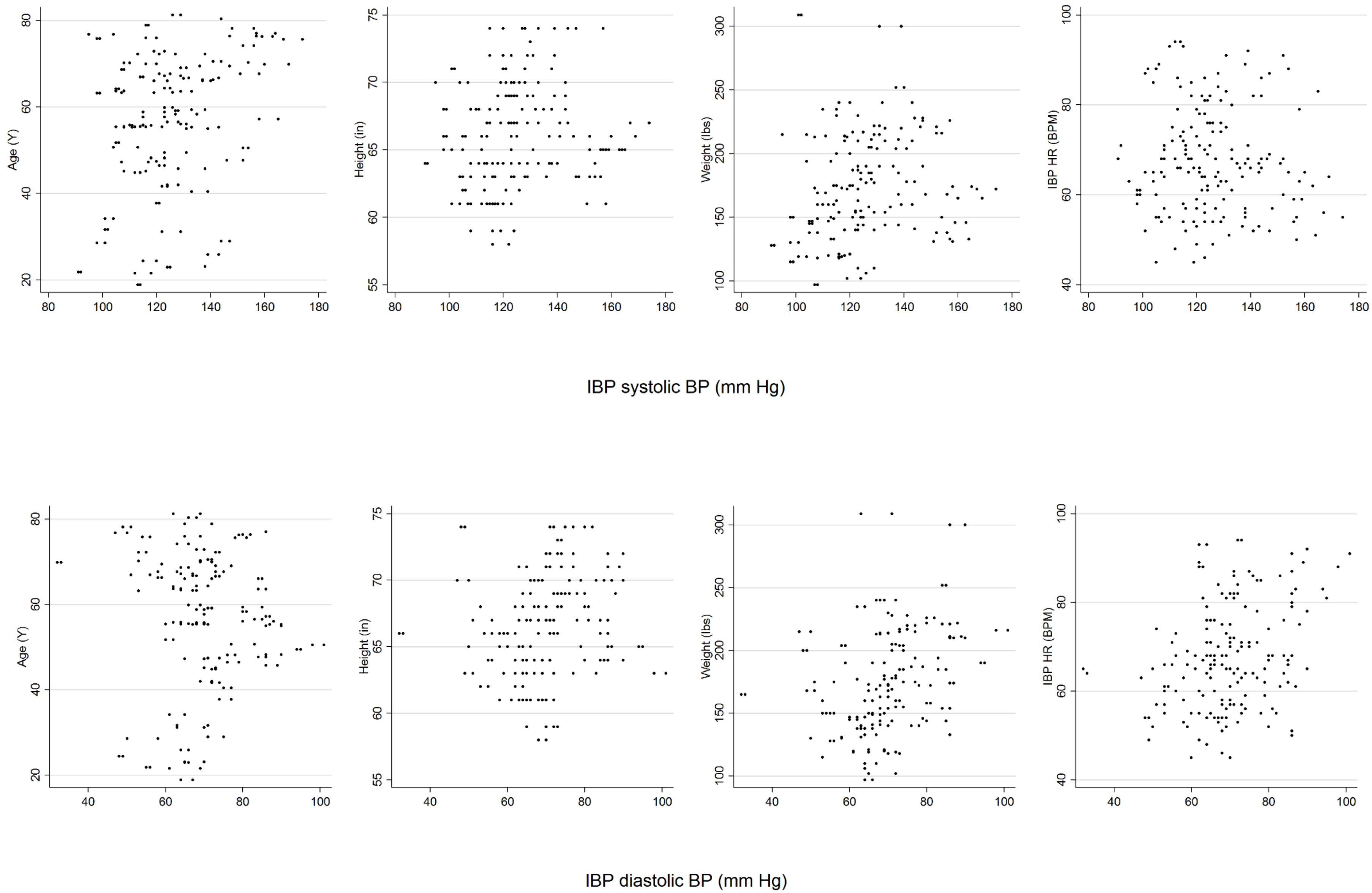
*Figure 11 - Bland-Altman Plot, IBP and Standard for HR**



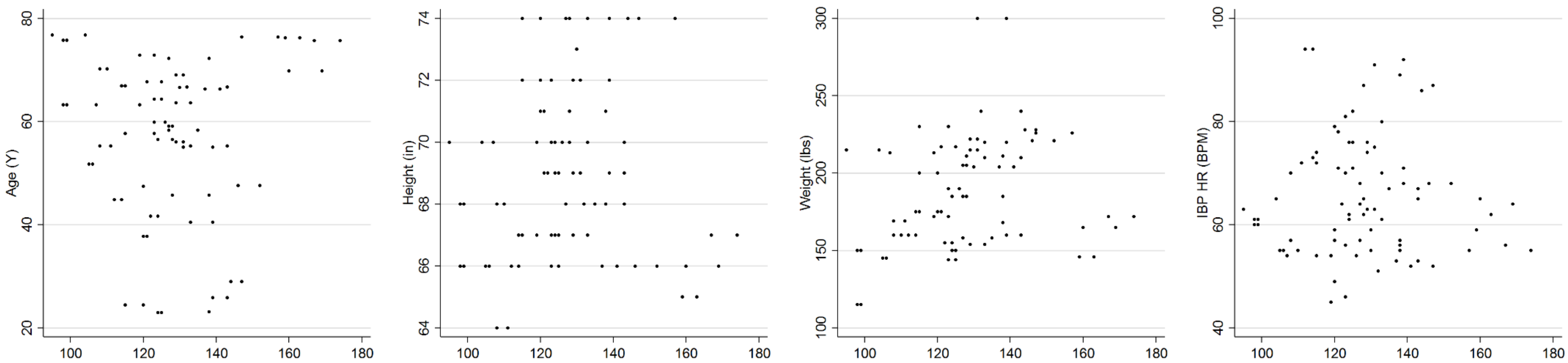
*The short dashed lines are the mean relative differences. The long dashed lines are ±2 SD.

Figure 12 - Scatterplots of age, weight, height, and HR versus IBP for systolic and diastolic BP measurements

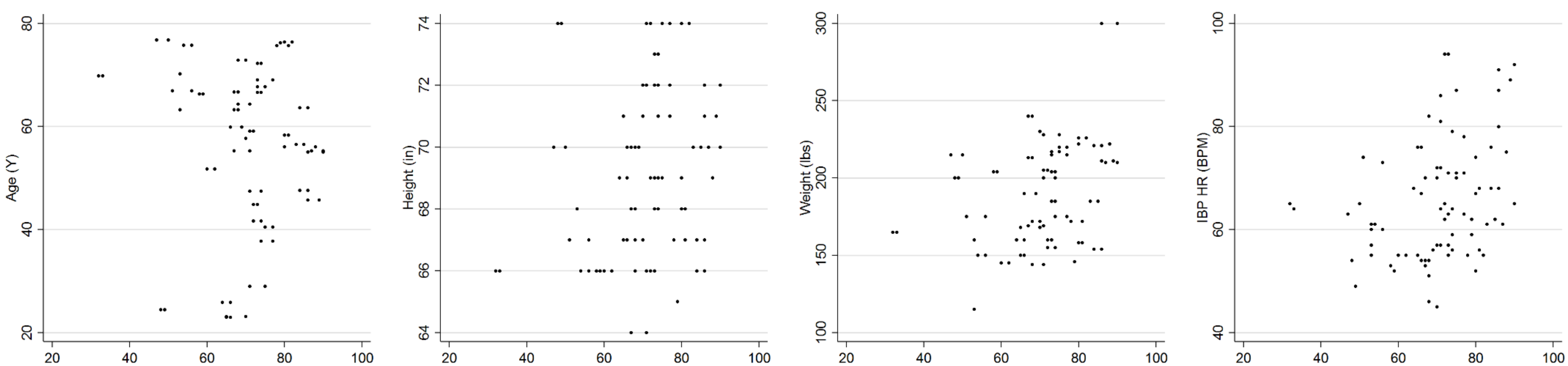
A) All participants



B) Males

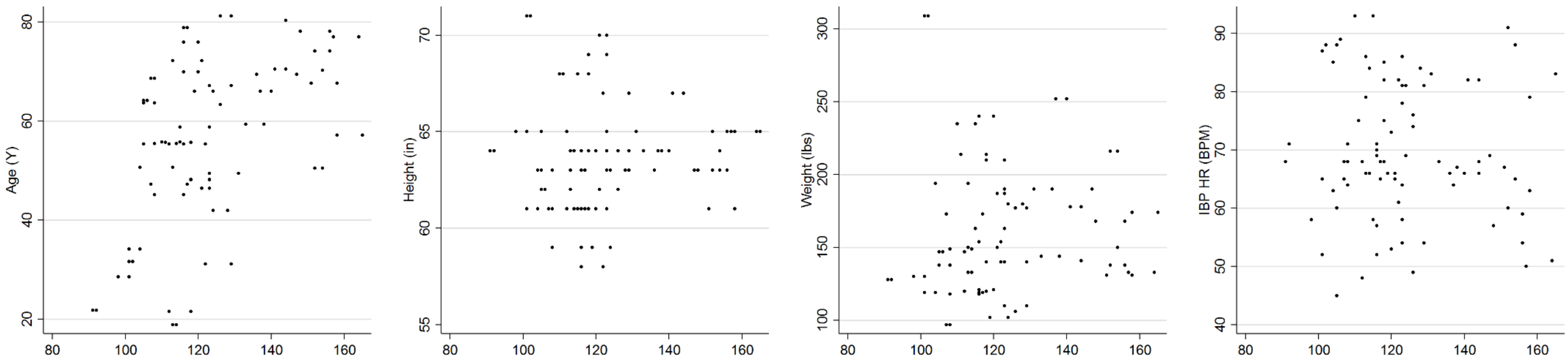


IBP systolic BP (mm Hg) among males

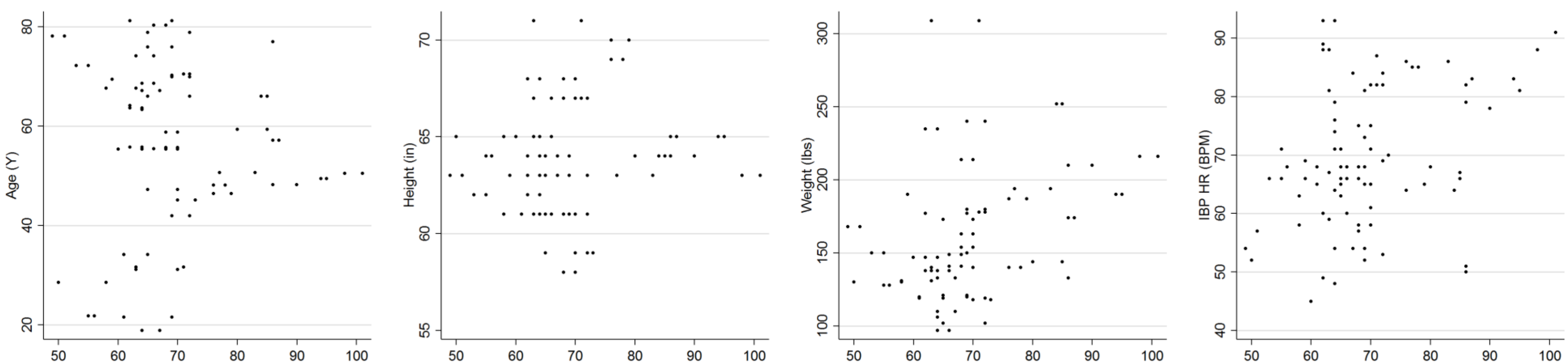


IBP diastolic BP (mm Hg) among males

C) Females



IBP systolic BP (mm Hg) among females



IBP diastolic BP (mm Hg) among females

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Curriculum Vitae

Demographic and Personal Information

Current Appointment

University:	Fellow, Division of General Internal Medicine
Work address:	Division of General Internal Medicine Johns Hopkins University 2024 East Monument St Suite 2-300B Baltimore, MD 21287
Phone:	Office: (443)283-9525 Pager: (410)283-7274
Email:	tplante1@jhmi.edu

Education and Training

Graduate

Year	Degree	Institution	Discipline
2006	Bachelor of Arts	University of Vermont	Zoology
2011	Doctor of Medicine	University of Vermont	Medicine
2016	Master of Health Science	Johns Hopkins Bloomberg School of Public Health Adviser: Larry Appel, MD MPH	Clinical Epidemiology

Post-doctoral

2011-2012	Internship	Georgetown University Hospital	Internal Medicine
2012-2014	Residency	Georgetown University Hospital	Internal Medicine
2014-present	Fellowship	Johns Hopkins University	General Internal Medicine

Research Activities

Research Publications

Peer-Reviewed Journal Articles

1. Plante TB, Iberri DJ, Coderre EL. Building a modern journal club: The Wiki Journal Club experience. Journal of Graduate Medical Education. 2015;7(3):341-343.
2. Urrea B, Misra S, Plante TB, Kelli HM, Misra S, Blaha MJ, Martin SS. Mobile health initiatives to improve outcomes in primary prevention of cardiovascular disease. Current Treatment Options in Cardiovascular Medicine. 2015;17(12):59.
3. Plante TB, Urrea B, MacFarlane ZT, Blumenthal RS, Miller ER, Appel LJ, Martin SS. Validation of the Instant Blood Pressure smartphone application (app). JAMA Internal Medicine. 2015; e-published 2016-03-02.

Letters to the Editor

1. Plante TB, Kane SP, Iberri DI, and Majure D. Clinical evidence summary apps: Definition, role, and unknown about a novel medical content delivery genre. Journal of Graduate Medical Education. 2014;6(4):791.

Oral Presentations

1. Hunter M, Plante TB, and Jemison J. The Consortium on Medical Education and Technology (COMET). Panelist. American Association of Medical Colleges Group on Information Resources, Burlington, VT. 2008.
2. Plante TB, Krolick K, Otsuki J, Gross N, and Manwell-Jackson A. Perspectives on the Future of Medical Education. Keynote panelist. American Association of Medical Colleges Group on Information Resources, Atlanta, GA. April 2009.
3. Plante TB and Littenberg B. Low-density lipoprotein cholesterol versus non-high density lipoprotein cholesterol in predicting mortality. Oral presentation. Society of General Internal Medicine of New England, Boston, MA, March 2011.
4. Plante TB and Iberri DJ. Open Access to Medical Knowledge: The Wiki Journal Club Experience. Poster Presentation. Georgetown Department of Medicine Research Day, Washington, DC. April 2013.
5. Plante TB, Chretien K, Desai S, and Brown S. The Next Generation's Information and Knowledge Needs. Panel. US BMJ Annual Meeting, Washington, DC, February 2014.
6. Plante TB. Wiki Journal Club and Journal Club for iPhone/Android. Oral presentation. Georgetown General Internal Medicine Educational Conference. Georgetown University Hospital, Washington, DC, April 2014
7. Plante TB. Patterns of visitation to a medical reference website from Google searches. Oral presentation. Georgetown Internal Medicine Grand Rounds. Washington, DC. May 2014.
8. Plante TB. Patterns of visitation to a medical reference website from Google searches. Oral presentation. Virginia Hospital Center Grand Rounds. Arlington, VA. May 2014.
9. Plante TB, Urrea B, MacFarlane ZT, Blumenthal RS, Miller ER, Appel LJ, Martin SS. Validation of the Instant Blood Pressure smartphone application (app). Oral presentation. American Heart Association Epidemiology. Phoenix, AZ. March 2016.

Poster Presentations

1. Trotman W, Madden M, Plante TB, Clay M, Mcilree C, and Bovill E. CADM1 plays a potentially important role in maintaining endothelial barrier function: Dynamic and selective expression of CADM1 in endothelial cells. Leducq International Network Against Thrombosis, Leuven, Belgium. May 2009.
2. Plante TB and Fung M. Challenges identified with Blood Bank ordering and documentation from an academic institution undergoing transition to an electronic health record (EHR). Academy of Clinical Laboratory Physicians and Scientists, Nashville, TN. June 2010.
3. Plante TB, Iberri DJ, Coderre EL, and Montero A. Patterns of visitation to a medical reference website from Google searches. Society of General Internal Medicine National Conference. San Diego, CA. April 2014.
4. Plante TB and Maruthur N. Journal Club mobile app usage in developing and developed countries. Society of General Internal Medicine National Conference. Toronto, ON. April 2015.

Invited Presentations

1. Plante TB. Validation of the Instant Blood Pressure smartphone application (app). Virginia Hospital Center Medicine Grand Rounds. Arlington, VA. March 2016. (Pending.)

Invited Online Commentary

1. Plante TB and Martin SS. App Review: The ACC-AHA ASCVD Risk Estimator. Practical Cardiology. April 2016. http://practicalcardiology.modernmedicine.com/practical-cardiology/news/app-review-acc-aha-ascvd-risk-estimator
2. Plante TB and Martin SS. How to pick your next health app. US News and World Report Health Blog. April 2016. http://health.usnews.com/health-news/patient-advice/articles/2016-04-28/how-to-pick-your-next-health-app

Research Projects

Date	Location/Collaborators	Subject	Role
2009	University of Vermont Department of Pathology Mark K Fung, MD PhD	Errors in EHR blood bank ordering	Investigator
2013-2014	Georgetown University Department of Medicine Alex Montero, MD MPH Stanford University Department of Medicine David Iberri, MD	Novel technologies in medical education	Investigator
2015-2016	Johns Hopkins University Division of General Internal Medicine PI: Seth Martin, MD MHS	Validation of the Instant Blood Pressure mobile app	Investigator
2015-Present	Johns Hopkins University Division of General Internal Medicine PI: Edgar Miller III, MD PhD	Novel recruitment for clinical trials	Investigator

Grants
T32HP10025B0 Institutional National Research Service Award

Educational Activities
Teaching

Date	Learners	Intervention
Classroom Instruction		
2014	3rd and 4th year medical students outpatient electives	Served as an Argy teaching resident, providing didactic content to medical students on their Georgetown inpatient and
2014-Present	JHH interns	Lead EBM didactic sessions.
2015-Present	1st year medical students	Small group faculty for epidemiology course.
2015-Present	3rd year medical students	Small group faculty for high value care curriculum course.
2016-Present	JH Bayview interns	Develop and taught evidence-based medicine lectures.
Clinical Instruction		
2015-Present	3rd year medical students	Teach fundamentals of clerkship work to ascending 3rd year medical students in Transition to Wards.

Distributed Instruction

2011-Present	Online	Developed Wiki Journal Club, an independent website providing unrestricted access to preappraised summaries and criticism of influential trials in medical literature. Also assisted in developing mobile applications to distribute content to these users.

Leadership Activities
2015-2016 Coordinator, Welch Center Grand Rounds Research Pearls
2015-2016 Committee member, Welch Center Website Renovation Committee

Clinical Activities
Certification
Medical Licensure
2014-present Maryland #D77388

Boards
2014 ABIM certified

Clinical Responsibilities
2014-present Johns Hopkins Greenspring Internal Medicine clinic, ½ day weekly
2014-present Medicine Consult Fellow, 4 weeks yearly
2015-present Hospitalist service coverage, as needed, typically 1-4 shifts monthly

Organizational Activities
Professional Society Memberships
2008-present American College of Physicians
2014-present Society of General Internal Medicine
2015-present American Heart Association

Professional Society Leadership
2016 Society of General Internal Medicine mHealth Interest Group leader

Editorial Activities
Journal Peer Review Activities
2015 Reviewer, Journal of Medical Internet Research

Recognition
Awards
2013, 2014 Nominee, String of Pearls Teaching Award
Department of Medicine, Georgetown University School of Medicine
Recognizing excellence in teaching medical students.

2014 Jerry I. Cherner Research Achievement Award in Resident Clinical Research Award
Department of Medicine, Georgetown University School of Medicine
Recognizing excellence in residency research.

2014 Hugh H. Hussey Teaching Award
Georgetown University School of Medicine
Recognizing excellence in residency teaching.

2014 Top Resident Teacher, Internal Medicine
Department of Medicine, VCU School of Medicine, Inova Fairfax Campus

Recognizing excellence in teaching medical students.

2014	Resident Teaching Award Department of Medicine, Georgetown University School of Medicine Recognizing excellence in peer education among residents, selected by peers.
2014	Resident of the Year Department of Medicine, Inova Fairfax Hospital Recognizing clinical and teaching excellence.
2016	W. Leigh Thompson Excellence in Research Award Department of Medicine, Johns Hopkins University School of Medicine Recognizing excellence in postdoctoral clinical research.
2016	Anna Huffstutler Stiles Scholarship Department of Epidemiology, Johns Hopkins Bloomberg School of Public Health Recognizing innovative thesis research.

Other Professional Accomplishments

2011-present	Co-founder and editor-in-chief of Wiki Journal Club
2013-present	Co-developer of Journal Club for Android mobile application